REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	19 July 2002	Annual Report 1 June 2001 - 30 June 2002

4. TITLE AND SUBTITLE
Adaptive Protocols for Mobile Wireless Networks

5. FUNDING NUMBERS
N00014-00-1-0565

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Office of Naval Research
Ballston Centre Tower One
800 N. Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20020724 086

13. ABSTRACT *(Maximum 200 words)*

Progress is reported on basic research in mobile wireless communication networks for tactical applications. Research results are presented on adaptive, energy-efficient, distributed protocols for mobile wireless networks that must operate effectively over unreliable communication links in highly dynamic environments. The dominant feature of the research is the exploitation of interactions among protocols to capitalize on the opportunities and overcome the impediments presented by the tactical communications environment. The interactions among protocols involve not only the exchange of information but also the active cooperation of different classes of protocols to accomplish the common objective of reliable, energy-efficient distribution of information. The research goals include establishing and taking maximum advantage of a strong coupling of the various protocol layers with such physical-layer functions as antenna array processing, receiver processing, modulation and demodulation, error-control coding, decoding, protocols for directional antennas, and broadband antennas for spread-spectrum communications. The development of side information in physical-layer operations and its effective utilization in adaptive protocols are fundamental elements of the adaptive protocols in our research.

14. SUBJECT TERMS	15. NUMBER OF PAGES
spread-spectrum, code-division multiple access, tactical cellular networks	10
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Annual Progress Report

18 July 2002

Title: Adaptive Protocols for Mobile Wireless Networks

Office of Naval Research Grant Number: N00014-00-1-0565
Funded under the MURI Program

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Abstract

Progress is reported on basic research in mobile wireless communication networks for tactical applications. Research results are presented on adaptive, energy-efficient, distributed protocols for mobile wireless networks that must operate effectively over unreliable communication links in highly dynamic environments. The dominant feature of the research is the exploitation of interactions among protocols to capitalize on the opportunities and overcome the impediments presented by the tactical communications environment. The interactions among protocols involve not only the exchange of information but also the active cooperation of different classes of protocols to accomplish the common objective of reliable, energy-efficient distribution of information. The research goals include establishing and taking maximum advantage of a strong coupling of the various protocol layers with such physical-layer functions as antenna array processing, receiver processing, modulation and demodulation, error-control coding, decoding, protocols for directional antennas, and broadband antennas for spread-spectrum communications. The development of side information in physical-layer operations and its effective utilization in adaptive protocols are fundamental elements of the adaptive protocols in our research.

Research Progress

The use of fixed transmission parameters for time-varying channels results in wasted energy when channel conditions are good. Adaptation of the power, code rate, and symbol rate reduces energy consumption and interference caused to other systems. Such adaptation requires information about the characteristics of the channel, which is more difficult to obtain in a packet-radio network or other mobile ad-hoc network than in a typical cellular communication system. We have devised techniques to provide partial information about the channel state in a direct-sequence spread-spectrum packet radio network, and we have designed and evaluated a protocol that uses this information to adapt the transmission parameters. We showed that our adaptive-transmission protocol is far superior to the use of fixed transmissions in wireless communications with time-varying propagation loss and interference. In addition, our adaptive-transmission protocol performs nearly as well as adaptive transmission with perfect knowledge of the previous state of the channel. This implies that the partial information developed in our approach provides an accurate measure of the channel quality, and very little can be gained by use of more complex measurements.

We have described and evaluated an energy-efficient routing protocol for frequency-hop wireless networks. The link resistance measures provide a protocol that accounts for energy consumption and link quality in the selection of routes in a wireless network that exhibits time varying propagation losses and interference. Several resistance measures have been devised, and performance comparisons have been completed. Tradeoffs among energy efficiency, delay, and packet success probability have been investigated. Our results demonstrate that if the routing protocol focuses primarily on energy conservation, the delay and end-to-end success probability may be unacceptable for many types of traffic. Our results also demonstrate that a compromise between energy conservation and delay performance can be achieved by the use of a hybrid quality-energy resistance measure. This resistance measure provides a tradeoff among throughput, energy conservation, delay, and end-to-end success probability.

We also developed and evaluated a new adaptive forwarding protocol, referred to as alt-forwarding. The alt-forwarding protocol assists the routing protocol by forcing some transmissions on less frequently utilized links, thereby updating the information about the state of these links. The alt-forwarding protocol makes special forwarding attempts in order discover new or improved links that can improve energy efficiency. We evaluated the alt-forwarding protocol in a mobile wireless network with group mobility, and we demonstrated that it substantially improves throughput efficiency and success probability.

A significant requirement for wireless military communications networks is support for voice communications among a group of personnel. Modern mobile networks must operate even when the terminals are not within direct communication range, therefore control must be distributed among the terminals. Distributed coordination is required to enable contention-free link-level multicast transmissions. We have developed new distributed algorithms that can adapt each terminal's transmission times so that multicast voice can be supported efficiently. A key feature of these protocols is that a terminal is required to collect only local information. The algorithms do not require coordination

among all terminals, thereby allowing the network to adapt to changes in network connectivity quickly and efficiently.

We investigated a class of turbo product codes for slow-frequency-hop spread-spectrum communications over channels with partial-band interference and thermal noise. Comparisons with previous results for other turbo codes have been completed, and we have shown that in some situations an off-the-shelf turbo product code achieves performance that is better than previously published results for parallel-concatenated turbo codes of approximately the same rate. It is also shown that the performance of the commercial decoder can be enhanced by the use of side information that we can derive from the demodulator. Our results obtained on turbo product coding in frequency-hop systems with test symbols demonstrate that the decoder performance improves if side information is provided by the demodulation of the test symbols. We have also examined the performance of a parallel decoder structure with multiple decoders in which at least one decoder uses side information and one decoder does not.

We generalized our development of concatenated codes based on parity-check codes and turbo codes to include multidimensional parity-check codes and nonprimitive turbo codes, and we showed that these codes outperform other known codes of similar complexity. We have developed a new incremental-redundancy hybrid ARQ scheme that retransmits the bits that are deemed unreliable by soft-output decoding algorithms, and we have shown that these techniques can provide performance approaching channel capacity. We have shown through simulation and analysis that the use of physical-layer multicast signaling in distributed networks can significantly improve the network throughput. We have also shown that channel error counts are an effective means of estimating channel quality when the type of channel is unknown and may include bursty noise, fading and/or jamming.

We have developed a new algorithm for block demodulation of arbitrary amplitude-phase shift constellations in channels whose characteristics change within a block. The algorithm outperforms other block detection techniques with comparable complexity. The algorithm also provides a reliability metric that can be used in adaptive signaling protocols. We have also investigated the performance of an adaptive pacing algorithm as part of a channel-access protocol for mobile distributed networks. The amount of pacing changes as a function of queue lengths and retransmission rates. The incorporation of this algorithm with adaptive routing has also been explored.

Progress has been made in the construction of permutation decoding sets for some classes of linear codes. This method of construction points the way to finding PD-sets for other classes of codes with good automorphism groups, and in particular some of the generalized Reed-Muller codes. The method of construction is algebraic, not computational. We are developing a new method for decoding Hermitian codes and more general class of codes constructed from algebraic curves over finite fields. This new method does not use majority voting, which is a key step in all the current decoding algorithms. It uses Grobner bases in a natural way and can decode with both errors and erasures. An efficient procedure for performing GMD decoding using Gao's algorithm has been demonstrated. As developed here the complexity for successive decoding trials

for GMD decoding has been significantly reduced. This reduction is due mainly to the fact that the interpolation polynomials for successive trials do not have to be recalculated for each trial, but are obtained as modifications of the previous interpolation polynomials.

We are investigating slot assignment based on service demands in TDMA-based mobile wireless networks with directional antennas. The ability to control the direction and power of a transmission allows for slot reuse at proximate nodes. The distributed slot assignment algorithm accommodates long-term slot reservations based on specific service requirements of applications as well as short-term reservations through contention for unreserved slots. We have implemented the algorithm and are in the process of evaluating its performance through simulation.

One research focus has been techniques for acquisition of direct-sequence spread-spectrum packet transmissions with radios using omni-directional or directional antennas in distributed packet radio networks. Both serial and hybrid algorithms for noncoherent acquisition have been evaluated, and the evaluation has been extended to account for multipath channels. The effect of the direct-sequence spread-spectrum chip waveform and the delay-locked loop characteristics on acquisition performance has also been examined. A simple method of digital processing has been developed that compensates for certain degradations caused by the AGC system.

Judicious insertion along an antenna element of lumped tuning circuits of prescribed impedance enables one to control the bandwidth and reduce the length of the antenna. To facilitate incorporation of a circuit in an antenna structure and to account for its presence in an integral equation analysis of the antenna, techniques have been developed for modeling such lumped loads. Distributed models have been devised for inductors and resistors inside the tubular elements of monopole and dipole antennas, and the capacitance due to the close proximity of the coil and the conducting tube has been accounted for fully. Accuracy of the models has been confirmed experimentally.

Personnel Supported

Faculty, Clemson University: Michael Pursley (PI), Carl Baum, Chalmers Butler, Shuhong Gao, Joseph Hammond, Jennifer Key, John Komo, Daniel Noneaker, Harlan Russell, Martha Steenstrup

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Faculty and Student Honors and Awards

Faculty Honors and Awards:
Three IEEE Millennium Medals, 2000
National Science Foundation CAREER Award, 2001
Three Clemson University Board of Trustees Awards for Faculty Excellence, 2001
Clemson University Board of Trustees Award for Faculty Excellence, 2002
Clemson University Alumni Award for Outstanding Achievement in Research, 2000
Clemson University Alumni Award for Outstanding Achievement in Research, 2001
Honorary Member, Golden Key National Honor Society, 2000
IEEE Communications Society Distinguished Lecturer, 2001-02

Graduate Student Awards:
AFCEA Fellowship, 2001
Clemson College of Engineering and Science Outstanding Graduate Researcher, 2001
Clemson University Outstanding Graduate Researcher, 2001
Two MIT Lincoln Laboratory Fellowships, 2002-03

Undergraduate Student Awards:
IEEE Region 3 Student Paper Competition, First Place, 2001

Publications:

Refereed Publications in Journals:

R. P. Brent, S. Gao, and A. G. B. Lauder, "Random Krylov spaces over finite fields," submitted to the *SIAM Journal on Discrete Mathematics.*

K. L. Clark, J. D. Key, and M. J. de Resmini, "Dual codes of translation planes," accepted for publication in *European Journal of Combinatorics.*

P. Ding and J. D. Key, "Minimum-weight codewords as generators of generalized Reed-Muller codes," *IEEE Transactions on Information Theory*, vol. 46, pp. 2152-2158, 2000.

P. Ding and J. D. Key, "Subcodes of projective generalized Reed-Muller codes spanned by minimum-weight vectors," accepted for publication in *Designs, Codes and Cryptography.*

S. Gao, "Abelian groups, Gauss periods, and normal bases," Finite Fields and Their Applications, vol. 7, pp. 149-164, January 2001.

S. Gao, "Factoring multivariate polynomials via partial differential equations," accepted for publication in *Mathematics of Computation.*

S. Gao, E. Kaltofen, and A. G. B. Lauder, "Deterministic distinct degree factorization for polynomials over finite fields," submitted to the Journal of Symbolic Computation.

S. Gao and A. G. B. Lauder, "Hensel lifting and bivariate polynomial factorisation over finite fields," accepted for publication in Mathematics of Computation.

S. Gao and V. M. Rodrigues, "Irreducibility of polynomials modulo p via Newton polytopes," submitted to the Journal of Number Theory.

J. H. Gass, Jr., D. L. Noneaker, and M. B. Pursley, "A comparison of slow-frequency-hop and direct-sequence spread-spectrum communications over doubly selective fading channels," accepted for publication in the *IEEE Transactions on Communications*, vol. 50, no. 8, August 2002.

J. H. Gass, Jr., M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "An adaptive-transmission protocol for frequency-hop wireless communication networks," *Wireless Networks*, vol. 7, no. 5, pp. 487-495, September 2001.

L. L. Joiner and J. J. Komo, "Errors and erasures decoding of BCH and Reed-Solomon codes for reduced M-ary orthogonal signaling," accepted for publication in the *IEEE Transactions on Communications.*

J. D. Key and M. J. de Resmini, "An upper bound for the minimum weight of dual codes of Figueroa planes," accepted for publication in *Journal of Geometry.*

J. D. Key, J. Moori, and B. G. Rodrigues "Some binary codes with automorphism group containing the symplectic group of odd characteristic," submitted to *Combinatorica.*

J. D. Key, J. Moori, and B. G. Rodrigues, "Binary codes of triangular graphs and permutation decoding," submitted to *Graphs and Combinatorics.*

T. G. Macdonald and M. B. Pursley, "Hermitian codes for frequency-hop spread-spectrum packet radio networks," accepted for publication in the *IEEE Transactions on Wireless Communications.*

T. G. Macdonald and M. B. Pursley, "Staggered interleaving and iterative errors-and-erasures decoding for frequency-hop packet radio," accepted for publication in the *IEEE Transactions on Wireless Communications.*

D. L. Noneaker, A. R. Raghavan, and C. W. Baum, "The effect of automatic gain control on serial, matched-filter acquisition in direct-sequence packet radio communications," *IEEE Transactions on Vehicular Technology*, vol. 50, no. 4, pp. 1140--1150, July 2001.

F. A. Pisano III and C. M. Butler, "Analysis of a cylindrical antenna containing an aperture coupled load," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 4, pp. 457-468, April 2002.

F. A. Pisano III and C. M. Butler, "Load approximations for a wire antenna loaded with a shielded network," accepted for publication in the *IEEE Transactions on Antennas and Propagation.*

F. A. Pisano III, C. M. Butler, and J. P. Rudbeck, "Analysis of a tubular monopole loaded with a shielded helical coil," accepted for publication in the *IEEE Transactions on Antennas and Propagation.*

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Metrics for energy-efficient routing in frequency-hop wireless networks," submitted to the *IEEE Transactions on Wireless Communications.*

M. B. Pursley, "Direct-sequence spread-spectrum communications for multipath channels," *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 3, pp. 653-661, March 2002.

M. B. Pursley and C. S. Wilkins, "Adaptation of code rate and transmitter power in frequency-hop communications," submitted to the *IEEE Transactions on Wireless Communications.*

S. D. Rogers and C. M. Butler, "An efficient curved-wire integral equation solution technique," *IEEE Transactions on Antennas and Propagation*, vol. 49, no. 1, pp. 70-79, January 2001.

S. D. Rogers and C. M. Butler, "Wideband sleeve-cage and sleeve helical antennas," accepted for publication in the *IEEE Transactions on Antennas and Propagation.*

S. D. Rogers, C. M. Butler, and A. Q. Martin, "Design and realization of GA-optimized wire monopole and matching network with 20:1 bandwidth," accepted for publication in the *IEEE Transactions on Antennas and Propagation.*

S. D. Rogers, C. M. Butler, and A. Q. Martin, "Realization of GA-optimized wire antenna with 5:1 bandwidth," *Radio Science*, vol. 36, no. 6, pp. 1315-1325, Nov./Dec.2001.

S. D. Rogers, J. C. Young, and C. M. Butler, "Monopoles loaded with coils: a comparison of measured and computed results," *Journal of EM Waves and Applications*, vol. 15, no. 6, pp. 833-857, 2001.

J. M. Shea, "Concatenated parity and turbo codes," *IEE Electronics Letters*, vol. 37, no. 16, pp. 1029–1030.

J. M. Shea, "Reliability-based hybrid ARQ," vol. 38, no.13, pp. 644-645, June 2002.

J. M. Shea and T. F. Wong, "Concatenated parity-check codes and turbo codes," submitted to *IEEE Transactions on Communications.*

T. F. Wong and J. M. Shea, "Multi-dimensional parity-check codes for bursty channels," submitted to the *IEEE Transactions on Information Theory.*

H. Wu, A. Hasan, I. F. Blake, and S. Gao, "Finite fields multiplier using redundant representation," submitted to the *IEEE Transactions on Computers.*

F. Xie, J. L. Hammond, and D. L. Noneaker, "Evaluation of a split-connection mobile transport protocol," submitted to *Wireless Networks.*

F. Xie, J. L. Hammond, and D. L. Noneaker, "Steady-state analysis of a split-connection scheme for mobile internet access," submitted to the *IEEE/ACM Transactions on Networking.*

J. C. Young and C. M. Butler, "Inductance of a coil in a slotted shield," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 4, pp. 475-484, April 2002.

J. C. Young and C. M. Butler, "Inductance of a Shielded Coil," *IEEE Transactions on Antennas and Propagation,* vol. 49, no. 6, pp. 944-953, June 2001.

Books and Chapters in Books:

T. G. Macdonald and M. B. Pursley, "Coding for slow-frequency-hop transmission: Variations on a theme of McEliece," in *Information, Coding, and Mathematics*, pp. 183-208, Kluwer, Boston, 2002.

M. B. Pursley, *Random Processes in Linear Systems*, Prentice-Hall, 2002.

J. M. Shea and T. F. Wong, "Multidimensional Codes," accepted for publication in *Encyclopedia of Telecommunications*, John Wiley & Sons.

Patents:

J. M. Shea, "Method and coding means for error-correction utilizing concatenated parity and turbo codes," US Patent applied for, Ser. No. 10/102,367, International application applied for, No. PCT/US02/08616, filed March 2002

Refereed Conference Publications:

F. N. Ali, P. K. Appani, J. L. Hammond, V. V. Mehta, D. L. Noneaker, and H. B. Russell, "Distributed and adaptive TDMA algorithms for multiple-hop mobile networks," accepted for publication in the *Proceedings of the 2002 IEEE Military Communications Conference* (Anaheim, CA), October 2002.

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F. D. Block and M. B. Pursley, "An adaptive transmission protocol for direct-sequence spread-spectrum packet radio networks," accepted for publication in the *Proceedings of the 2002 IEEE Military Communications Conference* (Anaheim, CA), October 2002.

J. P. Coon, T. G. Macdonald, and M. B. Pursley, "A new method for obtaining side information in frequency-hop spread-spectrum systems," *Proceedings of 2000 IEEE Military Communications Conference*, (Los Angeles, CA), vol. 1, pp. 5.2.1-5, October 2000.

L. L. Joiner and J. J. Komo, "Soft-decision decoding of nonbinary codes," *Proceedings of 2001 IEEE Military Communications Conference* (McLean, VA), pp. 48.3.1-5, October 2001.

J. J. Komo and L. L. Joiner, "Reed-Solomon decoding complexity using Gao's Algorithm," invited by *IEEE International Symposium on Information Theory*, July 2002.

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M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Alt-forwarding in mobile frequency-hop wireless networks," *2002 IEEE Wireless Communications and Networking Conference Record* (Orlando, FL), vol. 1, pp. 426-432, March 2002.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "An improved forwarding protocol for updating channel state information in mobile FH wireless networks," *Proceedings of 2001 IEEE Military Communications Conference* (McLean, VA), pp. 29.5.1-5, October 2001.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient protocols for mobile wireless spread-spectrum communication networks," *Proceedings of Sixth International Symposium on Communication Theory and Applications*, (Ambleside, UK), pp. 64-69, July 2001.

M.B. Pursley, H.B. Russell, and J.S. Wysocarski, "Energy efficient routing in frequency-hop radio networks with partial-band interference," *Proceedings of 2000 IEEE Wireless Communications and Networking Conference*, (Chicago, IL), vol. 1, pp. 79-83, September 2000.

M.B. Pursley, H.B. Russell, and J.S. Wysocarski, "Tradeoffs in design of routing metrics for frequency-hop wireless networks," *Proceedings of 2000 IEEE Military Communications Conference* (Los Angeles, CA), vol. 1, pp. 3.1.1-5, October 2000.

J. M. Shea and T. F. Wong, "Concatenated codes based on multidimensional parity-check codes and turbo codes," *Proceedings of 2001 IEEE Military Communications Conference* (McLean, VA), pp. 34.6.1-5, October 2001.

J. M. Shea and T. F. Wong, "Reduced-complexity decoding for concatenated codes based on rectangular parity-check codes and turbo codes," *Proceedings of 2001 IEEE Global Communications Conference* (San Antonio, TX), pp. 1031–1035, November 2001.

J. M. Shea, K. Sistla, and B. A. Davis, "Multicasting in the forward link of CDMA cellular systems," accepted for publication in *Proceedings of the 2002 IEEE Military Communications Conference* (Anaheim, CA).

A. Swaminathan and D. L. Noneaker, "Performance of serial, matched-filter acquisition with adaptive thresholds in direct-sequence packet communications," accepted for publication in *Proceedings of 2002 IEEE Military Communications Conference* (Anaheim, CA), October 2002.

T. F. Wong and J. M. Shea, "Using multi-dimensional parity-check codes to obtain diversity in Rayleigh fading channels," *Proceedings of 2001 IEEE Global Communications Conference* (San Antonio, TX), pp. 1210–1214, November 2001.

J. C. Young and C. M. Butler, "Analysis and Design of Shielded Inductors," Symposium Digest, pp. 2001 URSI International Electromagnetic Theory Symposium, Victoria, BC, Canada, May, 2001.